PREPARATION FOR IN-PILE TESTS OF A LEU NEW TYPE FUEL ELEMENT

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ABSTRACT

The irradiation tests in the core of the IR-8 reactor (RRC "Kurchatov Institute") are planned for checking and confirmation of serviceability of a new rod type fuel element intended for using in the research reactors. The experimental fuel assembly (EFA) design has been developed. It allows to test a fuel element bundle under the conditions close to those which will take place during operation of the rod type fuel elements in the full-scale IRT-MR type FA. The neutron-physical, thermal hydraulic and stress-strain calculations substantiating the operation safety and representativeness of EFA tests are presented in the report.

1. Introduction

The design of a new rod type fuel element has been developed for the unification of fuel elements of the research reactors and the low enriched uranium (LEU) usage [1,2].

The in-pile tests of fuel elements of two size types are planned to be carried out in the VVR-M and IR-8 reactors. The objective of lifetime tests is the serviceability check of full-scale rod type fuel elements with uranium dioxide of 19,75 % enrichment in aluminum matrix.

The results of substantiation of a possibility of experimental fuel assembly (EFA) testing in the IR-8 reactor core [3] are given in this paper. Now the renewal of the heat exchangers in a cooling system is made at the reactor. The reactor operation is planned to restart in the beginning of the following year.

2. Experimental assembly design

The experimental fuel assembly (Fig.1) consists of the end parts and a square shroud, in which 25-rod fuel elements are arranged by means of two guide grids. The special guide grids ensure the necessary attitude and array pitch of fuel elements in EFA. The gap between the fuel elements is ensured by means of spiral fins. The design of fuel element arrangement is shown in Fig.3 as two characteristic cross-sections along the assembly height. The spiral fins of the fuel element improve the coolant flow enhancement and heat transfer.

The EFA allows to insert a fuel bundle in a central part of any ITR-3M type FA of the IR-8 reactor (Fig.2) and to provide the irradiation conditions maximum closed to operation conditions of the rod type fuel elements in the full-scale IRT-MR type FA [4,5].

The main geometrical characteristics of fuel element and EFA are listed in Table 1.

Table 1. The Geometrical Characteristics

EFA	
Parameter	Value
Number of Fuel Elements in EFA	25
Area of Water Passage, mm^2	380
Heat Transfer Surface, m^2	0,23
Wet Perimeter, мм	484,4
Hydraulic Diameter, mm	3,14
Fuel Meat Volume, cm^3	74,2
Volume Fraction of Coolant, %	62

Fuel Element	
Parameter	Value
Fin Spin Pitch, mm	320
Fuel Element Height/Meat, mm	630/580
Circumscribing Diameter, mm	4,85
Cladding Thickness, mm	min 0,3
Fuel Element Area, mm^2	9,0
Fuel Element Perimeter, mm^2	15,6
Fuel Composition Area, mm^2	5,12

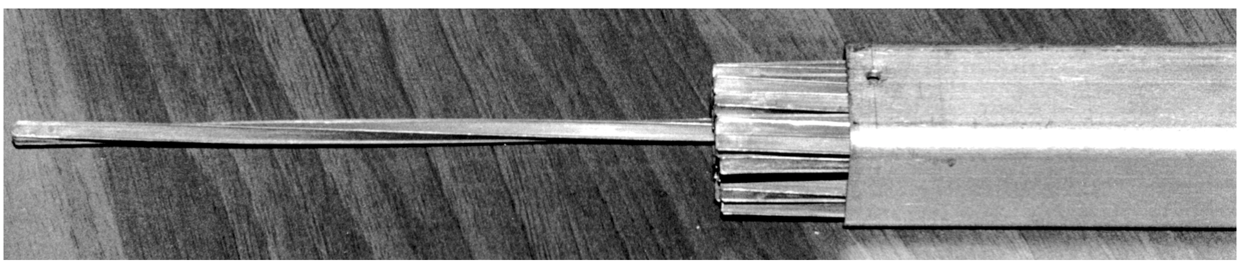


Figure.1. The experimental fuel assembly (EFA)

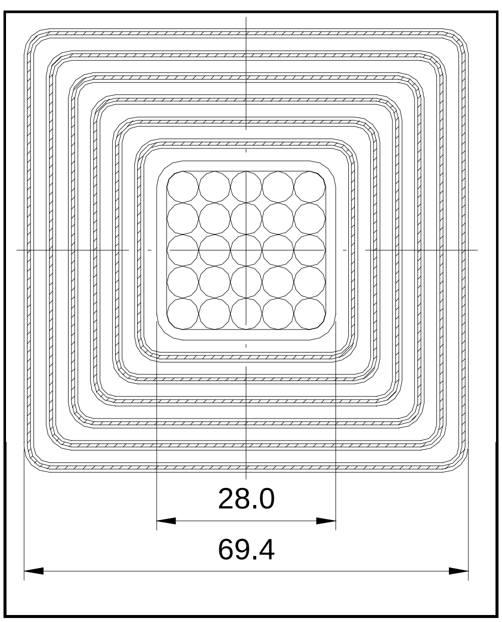
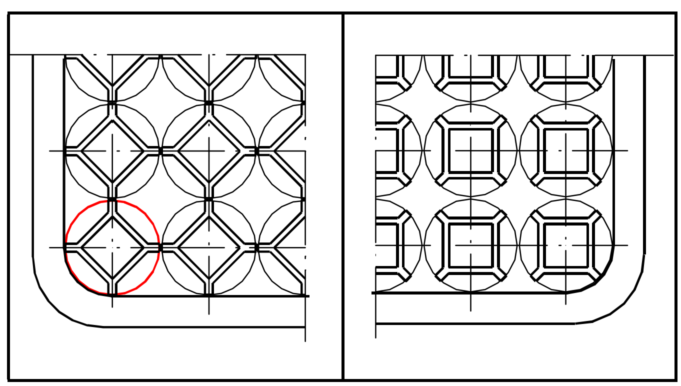


Figure.2.Complex assembly IRT-3M with EFA



Cross-section EFA (h_f - fin spin pitch)
a) H_{EFA}=1/4 h_f b) H_{EFA}= 1/8 h_f

Figure.3. Fuel Element Arrangement in EFA

The U_{235} loading in EFA is determined from the results of optimizing neutron-physical calculations of the IR-8 reactor core [6,7] with LEU dispersion (UO_2-Al) fuel. The core conversion variant has been selected on the base of following main criteria: 1) preservation of an equilibrium fuel cycle length with the sufficient core excess reactivity at the end of the cycle and the sufficient efficiency of CPS rods, 2) minimum reduction of the peak thermal neutron fluxes in experimental channels. The optimum characteristics of the core with LEU have been obtained for the case, when the U_{235} loading in six-tube IRT-3M FA is equal 352 g. Using this value the U_{235} loading in EFA is defined as 53,6 g, that corresponds to the rated uranium density in meat equal to 3,65 g/cm^3. Such uranium density is ensured by the UO_2 loading ~ 40 vol.%.

The main characteristics of fuel composition for current six-tube IRT-3M FA and EFA which differ in fuel enrichment and uranium density are given in Table 2.

Table 2. Dispersion Fuel Composition Characteristics

Fuel Assembly Type	U_{235} Loading in FA, g	U Density in Meat, g/cm^3	Fuel Enrichment, %	Volume Fraction UO_2, %	Heat-Conductivity Coefficient, W/m·°C (t=150°C)	
					τ=0	τ=1
IRT-3M	265	1,1	90	12	170	145
EFA	53,6	3,65	19,75	40	95	65

Note. τ = 0 – at the beginning of irradiation; τ= 1 – at the end of irradiation.

3. Determination of irradiation conditions of the EFA fuel elements

The neutron- physical and thermo-hydraulic calculations of the core and complex assembly consisting of six-tube IRT-3M FA and EFA (Fig.2) have been carried out for the development of in-pile test program, selection and substantiation of irradiation modes.

The neutron-physical calculations are performed for the case of core loading shown in Fig.4. The position of the shim-safety rod in the cells D-3, D-4 is 17 sm. The cell for EFA irradiation is chosen to provide the minimum duration of fuel element tests up to the average burn-up on EFA - 60 %, that corresponds to the average burn-up of current HEU six-tube IRT-3M FA. So the calculations of core are made under the condition that the IRT-3M FA with EFA is located in the cell E-2 (Fig.4), where its power is at maximum. The EFA is inserted into fresh IRT-3M FA at the beginning of the tests and is being irradiated there to the end of the tests.

The neutron-physical calculations were performed using IRT-2D/PC code [8] based on two-dimensional geometry in two-group diffusion approximation. The neutron cross sections (macroscopic physical constants) for calculated cells were computed using the URAN-AM [9] code and WIMS-SU [10] code. The procedures used for calculations were proved by the numerous experiments [11].

The basic results of calculations are presented in the Fig.5-6. The IRT-3M FA and EFA powers at the rated (N_r=8 MW) and lowered (N_l=5MW) operation modes of reactor are given in Table 3. The duration of fuel element tests up to average burn-up on EFA - 60 % will be ~ 275 eff. days.

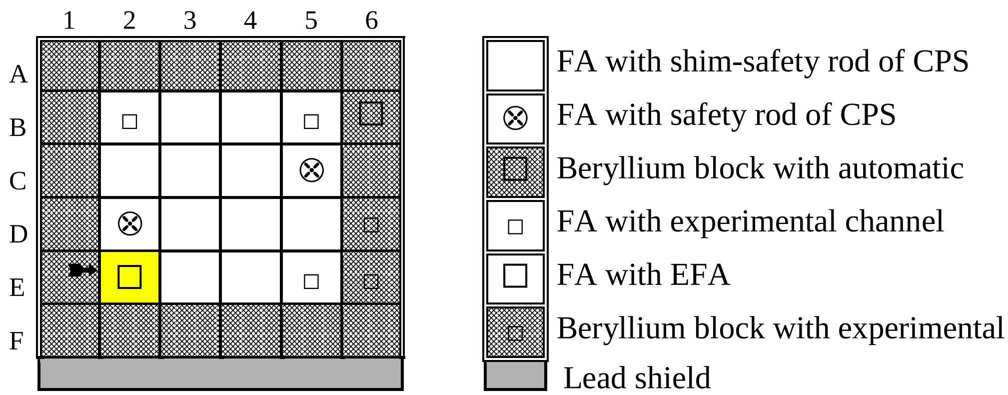


Figure.4. Loading of the IR-8 Reactor Core

a). irradiation beginning

	2	3	4	5
B	1.28 6.40	1.28 6.38	1.31 6.21	1.26 5.98
C	1.30 7.06	1.14 8.57	1.15 8.28	1.26 5.69
D	1.43 6.70	1.28 5.56	1.29 5.42	1.29 4.40
E	1.48 8.17	1.25 5.46	1.24 4.84	1.33 4.88

b). irradiation end

	2	3	4	5
B	1.29 6.58	1.28 6.64	1.31 6.51	1.27 6.29
C	1.30 7.12	1.14 8.81	1.15 8.62	1.26 5.97
D	1.43 6.60	1.29 5.56	1.31 5.55	1.30 4.56
E	1.41 5.99	1.24 5.34	1.21 4.85	1.35 5.00

Figure.5. $\dfrac{\text{Section power peaking factor } (Ks_{FA})}{\text{FA power in relative unit, } (\eta_{FA,}\%)}$

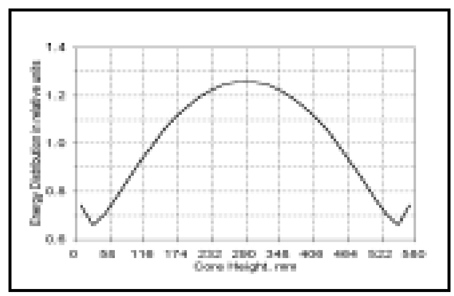


Figure.6. Energy distribution along EFA (K_z)

Table 3. FA Power

Mode of reactor operation		Power, kW	
		IRT-3M	EFA
N_l	$\tau = 0$	342,1	66,1
	$\tau = 1$	237,9	61,7
N_r	$\tau = 0$	547,3	105,8
	$\tau = 1$	380,6	98,8

The analysis of results of neutron-physical calculations has shown, that:

– Power of complex assembly IRT-3M FA with EFA increases by 13 %, and the energy liberation non-uniformity coefficient in its cross- section - by 6 %;

– The maximum value of the energy liberation non-uniformity coefficient in EFA cross-section is equal to 1,036 (maximum is located in a peripheral row) and almost does not vary during irradiation.

The results of neutron-physical calculations were used for substantiating of temperature conditions of irradiation of EFA rod fuel elements.

The main limiting factor of fuel element operation in this type of the reactor is the absence of surface boiling. So the fuel element cladding temperature is limited by the maximum value which should not be higher than the saturation temperature or the stated allowable value ($t_{cl}^{max} \leq t_a$). The multiple thermo-hydraulic calculations of the EFA were fulfilled for two reactor operation modes: lowered power (N_l) and rated power (N_r).

The code realizing the thermo-hydraulic calculation procedure for ring-like channels [12] was used for six-tube IRT-3M FA.

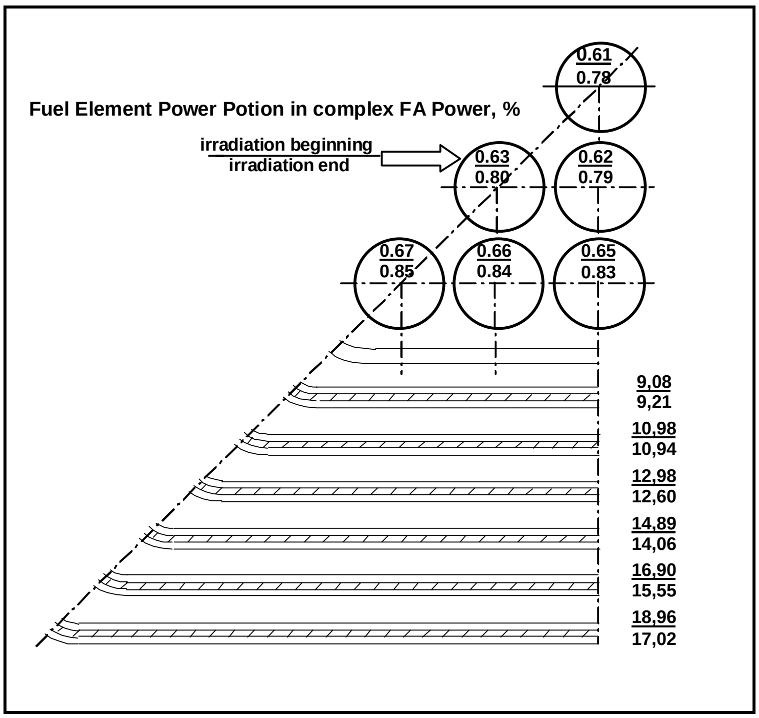


Figure.7. Calculation Model of Complex Assembly

Fuel assembly with rod type fuel elements constitutes a system of the interconnected channels having some intricate shape. The complex processes of coolant flow heat-mass interchange occur in them. These features of an assembly design require taking into account inter-channel mixing and heat transfer enhancement by spiral fins of fuel elements. Therefore the model of the elementary cells was used for the thermal hydraulic calculation of EFA.

This model has a set of empirical dependencies for inter-cell interaction coefficients. The dependencies generalize the large number of experimental data for single-phase fluid in FA channels with the rod type fuel elements. The following three mechanisms of inter-cell transfer in the cross-section of the assembly are taken into account in the model: convection, turbulent and conductive. The two-dimensional heat transfer in fuel element cross-sections of intricate shape is calculated using the numerical method of heat balances.

To take account of mutual influence of EFA and six-tube FA upon heat state the problem was solved in the conjugate statement. The cross-section of complex assembly (six-tube FA and EFA) used in calculations is given in Fig.7.

The initial data used in calculations (values of the input coolant pressure and temperature, pressure fall in core) are given in Table 5 [3]. The value of the coolant flow (Table 5) through EFA has been defined as a result of hydraulic tests of a simulated rod assembly [4]. The calculations of EFA with rod type fuel elements are executed at the nominal values of operating parameters and assumption that there is the ideal arrangement of fuel elements in the nodes of regular square grid with an average pitch (H_a). The value H_a is determined by nominal sizes of the fuel element, shroud and space between rods uniformly distributed in the assembly cross-section. The allowable cladding temperature is assumed to be 110°C with the saturation temperature margin and surface-boiling margin respectively equaled to 8°C and 24°C.

The basic calculated results are presented in Table 4 and in Fig.8-10. In Table 4 the max values of temperature of the most heated fuel element from each row of EFA and outer tubular fuel element from IRT-3M FA are given for the beginning and the end of tests. The max values of temperature ($t_{cl.av}$, $t_{cl.Max}$ и t_{max}) of the most heated fuel element located in an angular cell of EFA versus EFA power are shown in Fig.8. The temperature distributions at the height and perimeter of this fuel element are shown in Fig.9-10 for the most heated period of the irradiation (at the beginning of tests).

Table 4. Maximum Temperatures of Most Heated Fuel Elements

Mode of operation		Meat Temperature, °C				Cladding Temperature, °C			
	Type FE	Rod			Tubular	Rod ($t_{cl.max}/t_{cl.av}$)			Tubular
	№ row	1	2	3	outer	1	2	3	outer
N_l	$\tau = 0$	82	83	92	78	78/75	79/76	87/84	77
	$\tau = 1$	82	83	91	68	76/73	77/74	85/82	67
N_r	$\tau = 0$	101	103	116	94	94/91	95/92	109/105	93
	$\tau = 1$	101	103	115	80	92/88	93/89	105/101	79

Note. Fuel element rows in EFA is numbered from center to periphery.

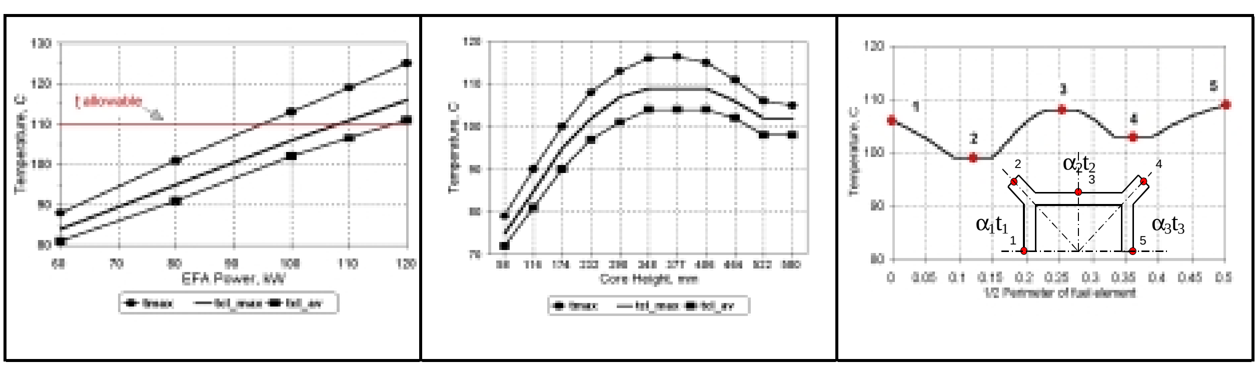


Figure.8. The maximum temperature of the most heated fuel element vs EFA power.

Figure.9. The temperature distribution along the fuel element height (N_{EFA}=106 kW).

Figure.10. The temperature distribution along the fuel element perimeter (N_{EFA}=106 kW).

Note. $t_{cl.av}$- the average value of cladding temperature along the fuel element perimeter.

The analysis of the temperature conditions of fuel elements in EFA which was made taking into account the local structure of coolant flow and energy distribution in the EFA volume has shown, that:

- energy liberation non-uniformity in the EFA cross-section and the presence of nonstandard geometry cells between fuel element and shroud results in the non-uniform distribution of coolant temperature in the assembly cells; the heating is higher in the assembly periphery than in the central area;
- taking into account the inter-cell heat transfer decreases the coolant temperature non-uniformity in assembly cross-section below ~ 35 % of coolant temperature in peripheral cells;
- taking into account the influence of six-tube FA on a thermal state of rod fuel elements in EFA results in the additional reducing (~ 10 %) of coolant temperature in peripheral cells due to heat transfer through a shroud of EFA;
- max temperature of fuel element cladding does not exceed the preset allowable value during the irradiation;
- allowable EFA power is estimated by the temperature of fuel element cladding located in angular peripheral cells and is equal to108 kW;
- max temperature of meat (t_{max}) 116°C is reached at a rated mode of reactor operation at the beginning of the irradiation and in the angular fuel elements of EFA; its value is nearly constant during the irradiation; along the fuel element height the t_{max} value varies in a range (80-116)°C at N_r and (60 – 90)°C at N_l.

The most heated irradiation conditions of fuel elements from EFA and six-tube IRT-3M FA at rated reactor power are given in Table 5.

Table 5. Main Irradiation Conditions of Fuel Elements

Parameter	Fuel Assembly Type	
	IRT-3M	EFA
Rated Reactor Power, MW	8	
Peak Power FA, kW	547	106
Input Pressure of Coolant, atm	1,9	
Pressure Fall, atm	0,25	
Input Temperature of Coolant, °C	47,5	
Output Temperature of Coolant, °C	68	77
Coolant Flow, m^3/h	25	3,05
Average Velocity, m/s	2,6	2,23

Maximum Heat Flux, MW/m^2	537	610*
Maximum Temperature of Meat, °C	94	116
Maximum Temperature of Cladding, °C	93	109 (105*)
Average burn-up in EFA, %	60	
Irradiation period, eff. day	275**	

Note. * - The average value along a fuel element perimeter;
** - The calendar time of tests will be defined by schedule of reactor operation.

In addition the estimation of the stress and strain of the fuel element from EFA in the most heated irradiation conditions was studied. The calculations were performed using MARC code [13] at the following conditions:

- for the the UO_2 loading ~ 40 vol.%;
- for the max of fuel burn-up – 80%;
- the max swelling of meat is assumed to be 6,4% /14/;
- the irradiation period is assumed to be 300 eff. day.

The basic calculated results are presented in Fig.11. The calculation results showed that the max strain of the cladding isn't exceed 3%. The max stress is below the yield stress.

The following basic parameters of hot forming are obtained:

- the max axial elongation is ~1%;
- the area of the fuel element in the most stress cross-section is increased at ~3%;
- the circumscribing diameter of the fuel element in the most stress cross-section is increased at ~1%.

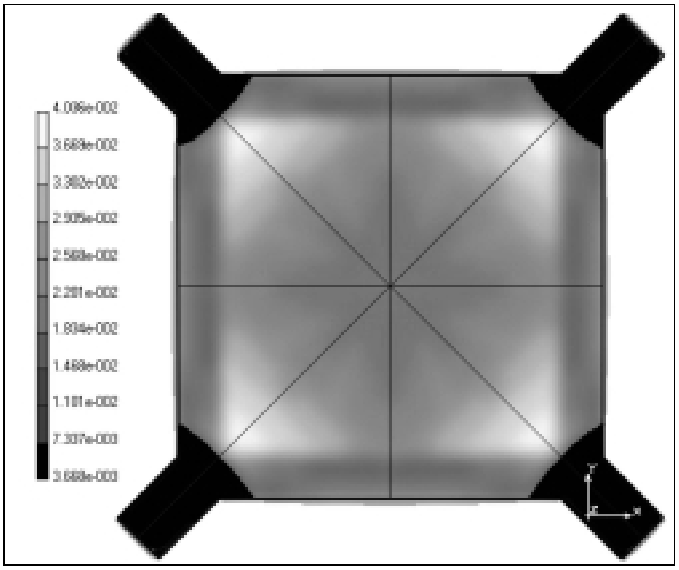


Figure.11. The strain distribution at the most stress cross-section of the fuel element

4. Conclusions

The neutron-physical, thermal hydraulic and stress-strain calculations of the EFA characteristics with the rod type fuel elements were fulfilled. The objective of calculations is the substantiation of testing possibility in the IR-8 reactor core and the ensuring of necessary conditions of tests.

The following results are obtained:

- irradiation conditions are close to the max operation conditions of the HEU tubular type fuel elements at a rated mode of the IR-8 reactor operation;
- during irradiation the maximum temperature of fuel elements will not exceed the assumed allowable value; the max swelling, stress and strain of the cladding are the small;
- the EFA operation conditions in cell E-2 of the core are safety and representative both for the substantiation of working capability of rod type fuel elements and the confirmation of design burn-up and lifetime.

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